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SLR2000 PROJECT: ENGINEERING OVERVIEW AND STATUS

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ABSTRACT

SLR2000 is an autonomous and eyesafe single photon satellite laser ranging station with an expected single shot range precision of about one centimeter and a normal point precision better than 3 mm. The system will provide continuous 24 hour tracking coverage. Replication costs are expected to be roughly an order of magnitude less than current operational systems, and the system will be about 75% less expensive to operate and maintain relative to the manned systems. Computer simulations have predicted a daylight tracking capability to GPS and lower satellites with telescope apertures of 40 cm and have demonstrated the ability of our current autotracking algorithm to extract mean signal strengths as small as 0.0001 photoelectrons per pulse from solar background noise.

SLR2000 consists of seven major subsystems: (1) Time and Frequency Reference Unit; (2) Optical Subsystem; (3) Tracking Mount; (4) Correlation Range Receiver; (5) Meteorological Station; (6) Environmental Shelter with Azimuth Tracking Dome; and (7) System Controller. The present paper provides an overview of the engineering design and status while other papers at this workshop, presented by members of the SLR2000 team, will provide additional detail on specific subsystems, algorithms, and software.

1. INTRODUCTION

SLR2000 is an autonomous and eyesafe satellite laser ranging (SLR) station with an expected single shot range precision of about one centimeter and a normal point (time-averaged) precision better than 3 mm [1-3]. The system will provide continuous 24 hour tracking coverage for a constellation of over twenty artificial satellites. Replication costs are expected to be roughly an order of magnitude less than current operational systems, and we estimate the system will be about 75% less expensive to operate and maintain relative to manned systems. Computer simulations have predicted a daylight tracking capability to GPS and lower satellites with telescope apertures of 40 cm and have demonstrated the ability of our current autotracking algorithm to extract mean signal strengths below .001 photoelectrons per pulse from daytime background noise.

The dominant cost driver in present SLR systems is the onsite and central infrastructure manpower required to operate the system, to service and maintain the complex subsystems, and to ensure that the transmitted laser beam is not a hazard to onsite personnel or to overflying aircraft. To keep development, fabrication, and maintenance costs at a minimum, we adopted the following design philosophies: (1) use off the shelf commercial components wherever possible; this allows rapid component replacement and "outsourcing" of engineering support; (2) use smaller telescopes (<50 cm) since this constrains the cost, size, and weight of the telescope and tracking mount; and (3) for low maintenance and failsafe reliability, choose simple versus complex technical approaches and, where possible, use passive techniques and components rather than active ones. Adherence to these philosophies has led to the SLR2000 design described here.

To achieve eye safety at the exit pupil of the telescope, the laser pulse energy is reduced by almost three orders of magnitude relative to current systems (from 100 mJ to 130 μJ) and the transmit beam is magnified to fill the available telescope aperture (40 cm). To compensate for this factor of 1000 reduction in signal strength, the repetition rate is increased from a nominal 5 Hz to 2 KHz (x 400) and the transmitter beam divergence is reduced from a nominal 25 arcseconds to about 10 arcseconds (x 6). The signal is extracted from the noise background using post-detection Poisson filtering To attain the same ranging accuracy, pulsewidths comparable to modelocked lasers must be maintained. All of the laser specifications

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can be met by a passively Q-switched microlaser, which is an exceedingly simple, highly reliable, and extremely small device (on the order of a few mm in length) and operates in a TEM_{00} mode [4].

A block diagram of the SLR2000 system is shown in Figure 1. SLR2000 consists of seven major subsystems: *(1) Time and Frequency Reference Unit; (2) Optical Subsystem; (3) Tracking Mount; (4) Correlation Range Receiver; (5) Meteorological Station; (6) Environmental Shelter with Azimuth Tracking Dome; and (7) Real-Time System Controller.*

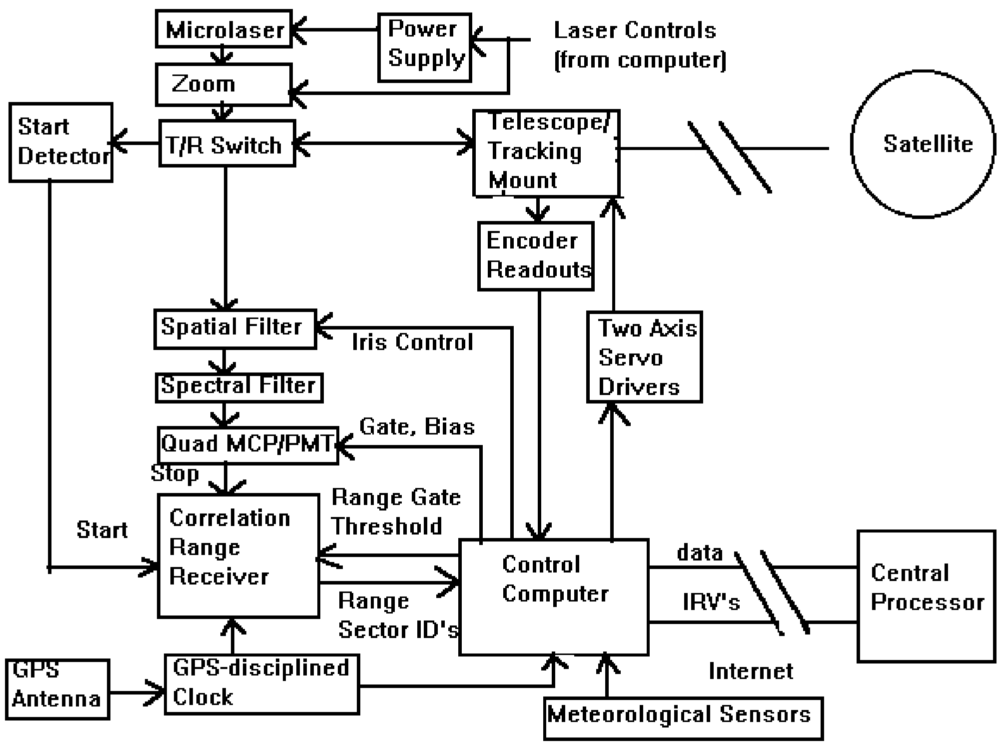

Figure 1: Simplified block diagram of the SLR2000 system.

As will be reported here, much progress has been made in the design, fabrication, and test of the prototype hardware. Some small deviations from previously planned approaches [1-3] have taken place as new enhancing technology became available or as encountered technical difficulties forced a somewhat different or more efficient approach. The present paper provides an overview of the engineering design and status while other papers at this workshop [4-10] will provide additional detail on specific subsystems, algorithms, and software.

2.0 SUBSYSTEM STATUS

2.1 Time and Frequency Reference

The purpose of the Time and Frequency Reference is twofold: (1) to provide accurate on-station epoch timing to simplify and accelerate the acquisition and tracking of the satellite targets; and (2) to provide an accurate frequency source for the pulse time-of-flight measurements. After testing several new timing units, we have selected the True Time Model LPFRS GPS-aided Rubidium oscillator and Model 151-358 GPS Synchronized Time and Frequency Receiver to serve as the prototype station clock and frequency reference for SLR2000. The unit uses timing information from the Global Positioning System (GPS) constellation of satellites to automatically constrain the long term frequency drift in a rubidium oscillator, has improved stability relative to the GPS-steered quartz oscillator considered previously [1-3], and is only slightly more expensive.

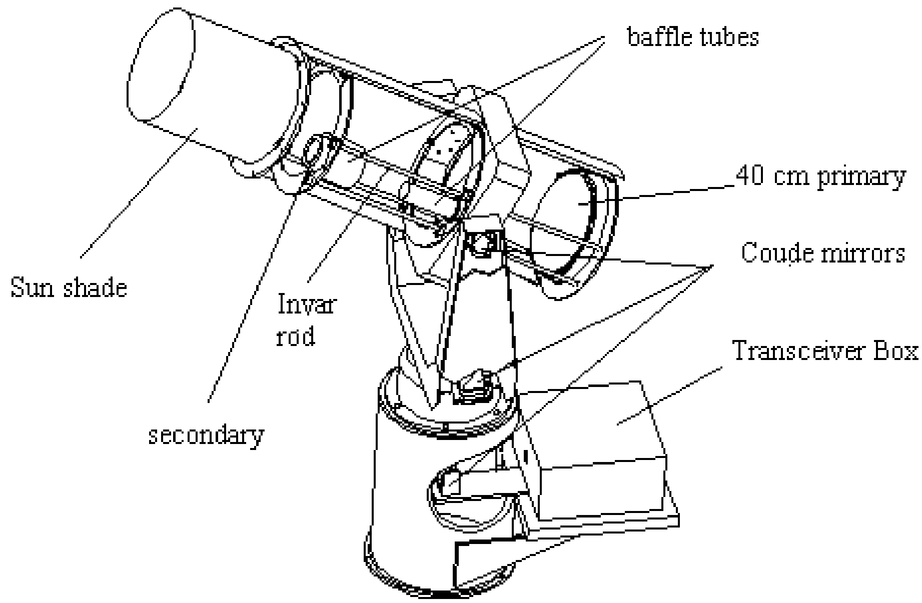

Figure 2: Cutaway view of SLR2000 telescope, tracking mount and transceiver box.

2.2 Optical Subsystem

The Optical Subsystem consists of a 40 cm diameter off-axis parabolic reflector telescope and an Optical Transceiver coupled via a transmitting Coude mirror assembly in the tracking mount as shown in Figure 2. An off-axis reflective design was chosen so that the transmitter could utilize the entire aperture thereby increasing the transmitted energy and eliminating the potentially harmful effects of a central obscuration on the transmitter throughput and far field pattern. An alternative refractive (lens) design was rejected because of the wide range of ambient temperatures (-8°C to 55°C) over which the telescope was expected to operate unassisted and the need to maintain good image quality (<2 arcsec) in a coaligned star camera over a sizable spectral bandwidth.

Good passive thermal stability is achieved in the telescope through the use of Zerodur primary and secondary mirror blanks and four Invar stabilizing rods which maintain the mirror spacings. A computer-controlled lens in the transceiver allows the system focus to be further optimized under either day or night conditions using star images. During star calibrations, collimated starlight is focused by a lens onto an Electrim Model EDC-1000M CCD array (see Figure 3) which measures the position of the star and provides pointing error information to the system computer for periodic mount model updates and pointing verification. The CCD array is also used to periodically check and verify accurate system focus by minimizing the diameter of the star image. During the day, the system can see stars of magnitude 2.5 or brighter.

A block diagram of the Optical Transceiver is shown in Figure 3. The transceiver is located in the temperature controlled room in the SLR2000 facility whereas the telescope and Coude optics are exposed to an ambient environment.

The beam from a passively Q-switched, frequency-doubled Nd:YAG microlaser [4] operating at 2 KHz enters a 9-power magnification telescope, passes through a polarizer, is rotated in polarization by a half-wave KD*P electro-optic Q-switch so that it reflects off the second polarizer, and enters a second motorized telescope assembly which controls the final beam divergence and optimally fills the exit pupil of the telescope with the transmit beam. A start detector photodiode views transmitter leakage through the point-ahead mirror and starts the range measurement. The point-ahead mirror steers the transmit beam forward along-track relative to the receiver axis since the beam divergence is only 10 arcseconds but the satellite can be displaced by up to 11 arcseconds during a pulse roundtrip transit time. A motorized variable neutral density filter wheel permits the transmitted and received beams to be strongly attenuated during ground calibrations to external targets.

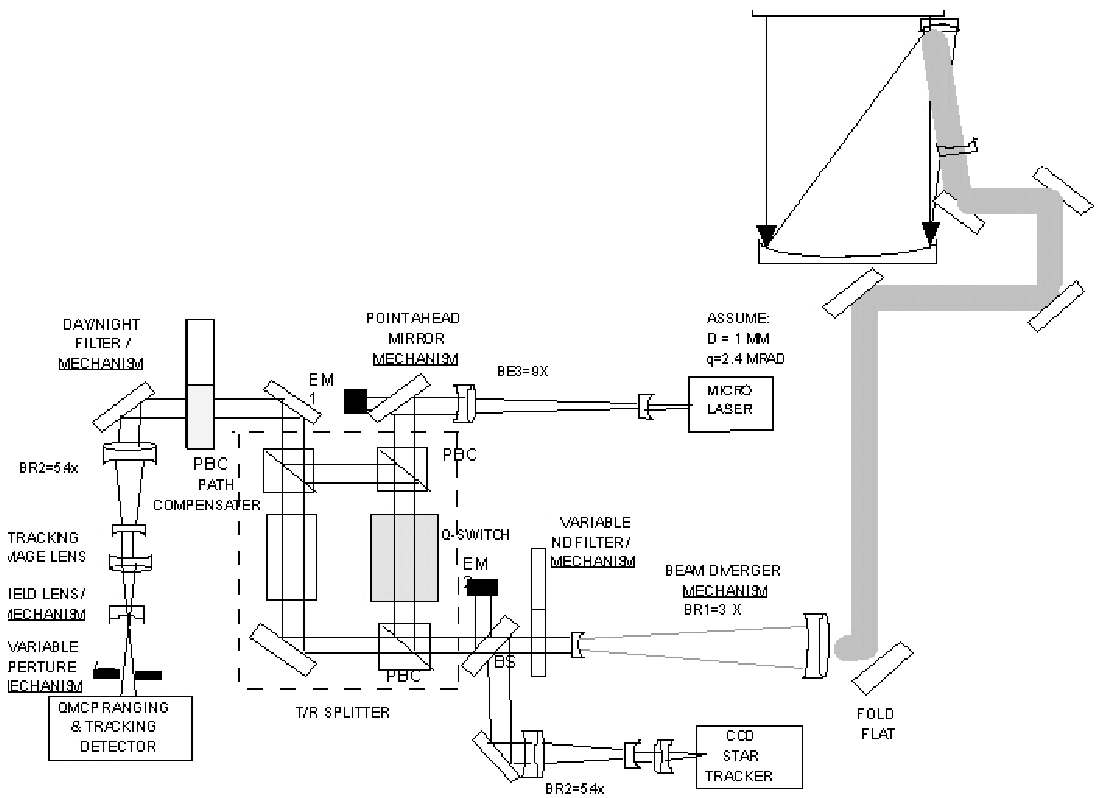

Figure 3: SLR2000 optical block diagram.

Depending on polarization, the return signal beam splits into two paths at the first polarizer in the T/R switch and, with the half-wave voltage now off, both polarization components are transmitted with high efficiency to the ranging and tracking detector. A compensator block in the second (passive) path matches the optical length to that of the active path so that both polarization components of the optical pulse arrive simultaneously at the ranging and tracking detector. The latter is a developmental photon-counting quadrant microchannel plate photomultiplier (MCP/PMT) built for SLR2000 by Photek Inc. detector (see Figure 4). It is placed behind the telescope focal plane so that the incoming reflected laser energy and background noise is spread over all four quadrants, allowing estimation of the position of the satellite in the receiver field of view by the correlation range receiver. Mechanized spectral and spatial filters in the receiver path control background noise levels.

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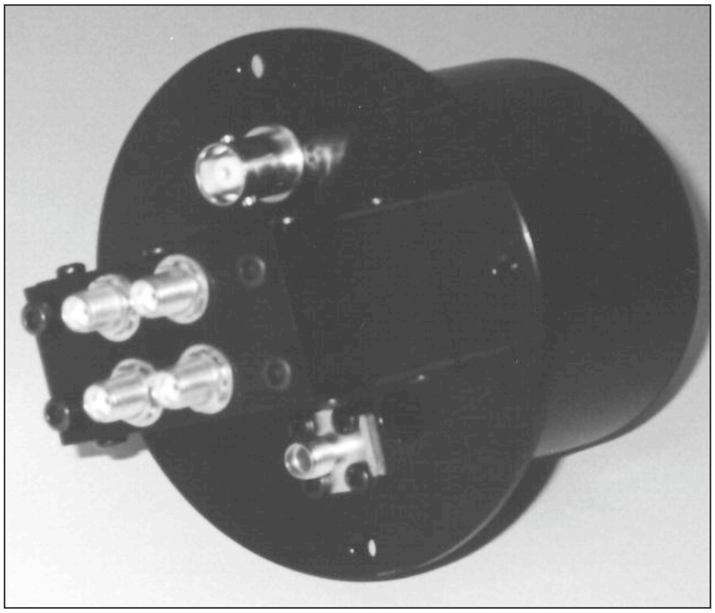


Figure 4: Prototype SLR2000 Quadrant Microchannel Plate Photomultiplier built by Photek Inc. The four SMA anode outputs can be seen at the left of the photo. The detector also has connections for the high voltage bias (top center) and kilohertz gating signals (bottom center).

Originally, we had planned to use a totally passive T/R switch, but all of the passive options were found to present serious technical problems ultimately traceable to either tracking mount costs and/or eye safety issues. A simple 50/50 passive beam splitter approach would reduce signal strength by a factor of 4 (equivalent to reducing the telescope diameter by a factor of 2), although half of this difference could be made up with a two-fold increase in laser power without exceeding eye damage thresholds. Spatial sharing of the 40 cm diameter aperture would result in a similar four fold decrease in signal strength which could not be recovered without going to larger or multiple telescopes and correspondingly larger tracking mounts. A simple polarization switch [1] would work well on most satellites but would require two large (10 cm diameter) and expensive compensating zero-order waveplates on each gimbal axis in order to counter depolarization effects in dielectric coatings or overcoats on the Coude mirrors. Unfortunately, these additional optics would not compensate for the depolarization that randomly occurs for satellites with uncoated Total Internal Reflection (TIR) retroreflectors, such as LAGEOS I and II. Our analysis and laboratory experiments suggest that significant fading of LAGEOS returns could occur. Use of another passive option, the wavelength switch [2,3], is thwarted by the fact that the low energy of the microlaser forces us to use small diameter beams in the doubling crystal in order to achieve high conversion efficiencies and this in turn leads to receiver field of view problems.

2.3 Correlation Range Receiver

Like the microlaser transmitter, the correlation range receiver (CRR) must also operate at KHz rates. All timing outputs from the CRR (starts, stops, and noise events) within a given range gate are transferred to the SLR2000 ranging computer which assigns them to *range bins*. Signal counts from the satellite are bunched in a narrow time interval whereas dark current or background noise counts are spread over the full width of the range gate. The number of pulses over which the returns are counted is determined by the *frame interval.* The 2D area in Observed Minus Calculated (O-C) range space bordered in the vertical by a *range bin* and in the horizontal by a *frame interval* is called a *cell*.

As the frame interval is made longer, more noise collects in the cells, and the signal itself may eventually spill into an adjacent bin due to imperfect orbit predictions or onsite time bias. If the frame time is too short, there may be not enough signal returns to reliably discriminate against the noise background. When the range bin width and frame interval are correctly chosen, the satellite returns will all fall within a single cell , resulting in a signal cell count that is significantly larger than that in cells where only noise counts occur. Thus, signal identification is made by applying a threshold test on the number of counts within the cell. Following the filtering of noise counts based on time of arrival by this postdetection Poisson filter, a subarcsecond pointing angle correction can be computed by adding or subtracting the residual (i.e. unedited) counts in each quadrant since the CRR also identifies which of the four quadrants the photons came from [2,3].

We previously described a baseline CRR for SLR2000 built up entirely from commercial nuclear timing components [2,3]. Subsequent tests of the CAMAC-based baseline device carried out in our laboratories were quite good and yielded a single shot noise floor of about 4 mm (one sigma RMS). However, in parallel, we developed enhanced versions of the Range Gate Generator and Event Timer based on state-of-the-art components developed for the Matera Laser Ranging Observatory (MLRO) by Allied Signal Technical Services (ATSC). Figure 5 describes the characteristics of the enhanced SLR2000 CRR which has a noise floor less than 1 mm.

(a) SLR2000 Range Gate Generator Characteristics:

Channels: 4 independent channels, upgradable to 8

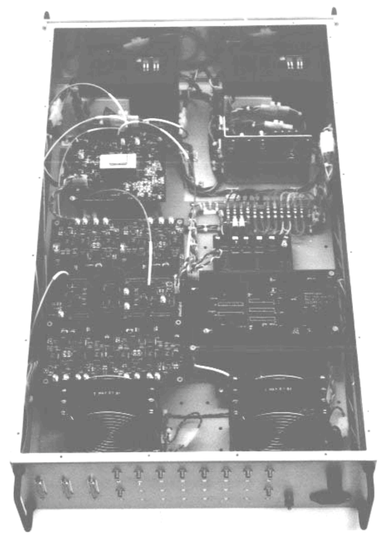
Channel Resolution: 20 ps leading edge, 500 ps trailing edge

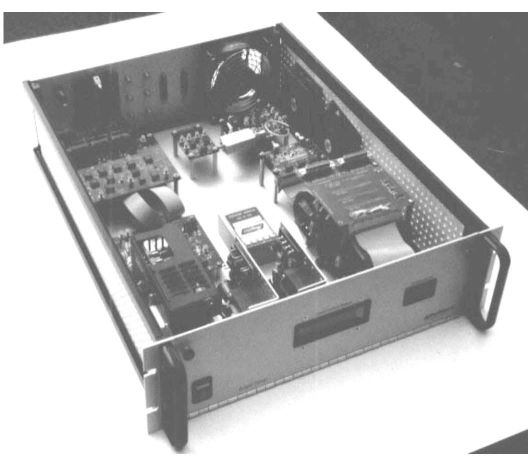
Coarse Clock: 250 MHz

RMS Jitter: < 50 ps (typically about 20ps)

Range: 20 ns to infinity

Update Rate: Multiple MHz (limited by computer interface)





(b) SLR2000 Enhanced ET Characteristics

RMS Jitter: <5 ps (calibrated)

Max Event Rate: 10 MHz Burst with duration limited
by computer

Internal Data Buffer: 500 events

Quad Input with Digital ID of input port

Internal Coarse Clock 500 MHz

12-bit A/D sampling over 2 ns period

Figure 5: (a) Enhanced SLR2000 Range Gate Generator photo and characteristics; (b) Enhanced SLR2000 Event Timer photo and characteristics.

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2.4 Simulators

The SLR2000 Software Simulator [11] permits testing of autotracking algorithms prior to hardware development. It models the relevant errors in the timing, tracking, receiver, laser and environment. The outer shell of the program keeps track of which returns are signal and which are noise and is therefore able to correctly assess the performance of the autotracking algorithms. Output is displayed in the form of an Observed minus Calculated (O-C) plot of the range data. Figure 6 shows the Correlation Range Receiver Single Frame Algorithm performance for a daylight pass of the LAGEOS satellite. Small dots indicate noise and darker squares are signal. Due to unmodeled errors in the mount pointing as well as small orbit prediction errors, the algorithm must first search for the satellite by scanning angularly. During the first 70 seconds, the system conducts a spiral scan searching outward from the satellite's predicted position, which the simulator purposely caused to be in error by about a beamwidth. It is important to note that during this period the algorithm does not mistake noise for signal. Once the algorithm finds satellite returns, it calculates the required biases to center both the range returns in the window and the laser beam on the satellite. The CRR acquires the signal quickly following initial illumination of the target (about 75 seconds into the pass), recognizes and corrects for a range bias of 0.5 μsec to center the signal in the gate, and continually narrows the width of the range gate from an initial value of $\pm$ 1 μsec until the background noise is nearly eliminated 140 seconds into the pass. In addition to the Software Simulator, a Hardware Simulator exercises the actual ranging hardware by simulating start and stop pulses using a short pulse diode laser under computer control.

2.5 Tracking Mount

Originally, we had planned to use an Aerotech Model AOM360-D tracking mount. . The latter mount has a high axis positioning accuracy of one arcsecond, a bidirectional repeatability to one arcsecond, and a low axis wobble, also at the few arcsecond level. However, the added requirement of tracking GPS and GLONASS led us to a larger telescope than originally planned (40 cm vs 30 cm), and the telescope size, weight and inertia now exceed the Aerotech specifications. Fortunately, we have identified several other vendors capable of building the required mount at a reasonable price. The use of inductosyns and resolvers, rather than optical encoders, for angle sensing retains the arcsecond resolution and accuracy but allows the 3 to 4 inch diameter laser beam to be passed from the transceiver to the telescope through the center of the azimuth and elevation drive bases via a Coude transfer system as in Figure 2. This arrangement provides the greatest flexibility in the prototype design.

2.6 Controller

The SLR2000 controller consists of three Pentium-based processors, two UNIX-based processors in a VME backplane and the third in a PC/ISA crate. The VME bus was chosen for its higher bus speed (40MB/sec), while the ISA bus was needed to handle specialized interface cards for key components. The ISA computer functions as an Input/Output processor, passing data to and from the VME computers via shared memory. The VME processors perform all of the decision making, data analysis, and external communication. One of these processors, the "Pseudo-Operator", performs the functions of a human operator, making decisions on whether the weather permits opening the dome and tracking, which satellite should be tracked, and whether the returns in the ranging window are signal or noise. The Pseudo-Operator also acts to protect the system if it detects system health or safety problems. The second VME processor, called the Analysis CPU, processes and exchanges range and orbit prediction data with the central network archive. Human interaction with the SLR2000 system requires communicating with the Analysis CPU through the internet. A laptop PC running a special software package will allow onsite maintenance personnel to monitor the operation of the system via graphical displays, get information from the system to analyze off-line, run diagnostic tests, and change system parameters. The computer subsystem and software packages are described in detail elsewhere in these proceedings [5-9].

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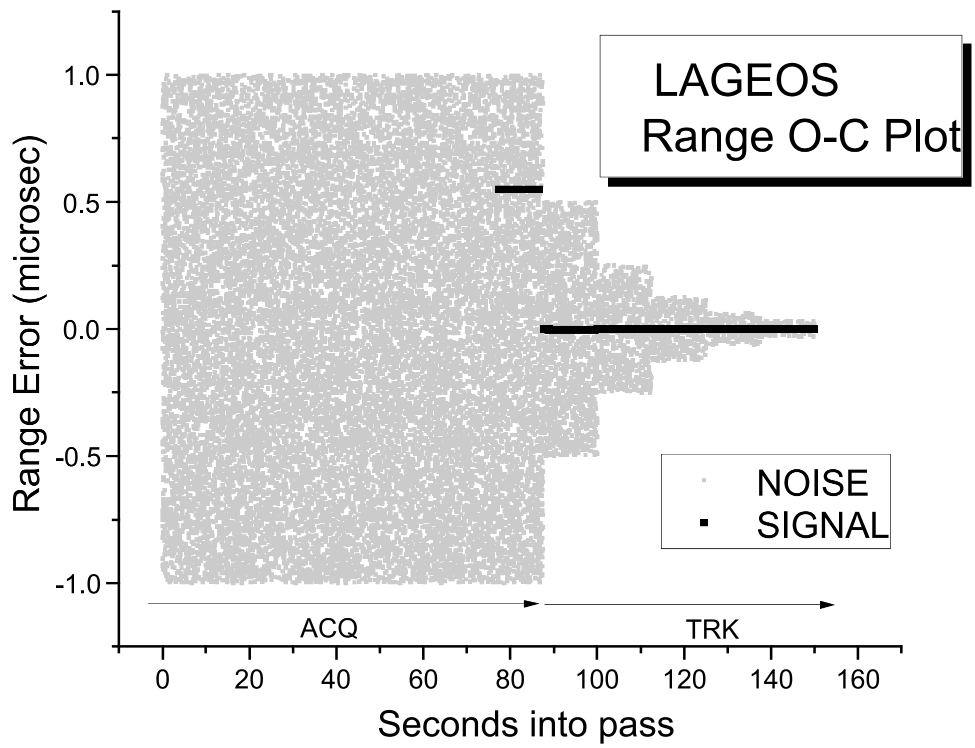

Figure 6: Simulated performance of SLR2000 acquiring the LAGEOS satellite in full daylight at an elevation angle of 20 degrees.

2.7 Meteorological Subsystem

The meteorological subsystem consists of four major components as in Figure 7. A Paroscientific MET3-1477-001 Pressure, Temperature, and Relative Humidity Monitor measures pressure, temperature, and relative humidity with the requisite accuracy for supporting atmospheric models used in applying the atmospheric correction in subcentimeter laser ranging. The Belfort 200 Wind Monitor measures wind speed and direction. The Vaisala FD12P Precipitation and Visibility Sensor monitors the presence, type, and accumulation of various forms of precipitation (rain, snow, etc.);as well as local visibility out to 50 Km. Finally, an Inframetrics Thermasnap^{TM} camera, containing an uncooled silicon thermoelectric IR detector array operating between 8 and 12 microns, is placed above a convex mirror overcoated with gold in order to photograph the full sky cloud cover, day or night, nearly to the horizon in a single frame. Each pixel senses the temperature of the sky within its field of view. Low lying cumulus cloud temperatures tend to follow the lapse rate with altitude and hence are at significantly higher temperatures (10-20^{o}C) than the higher cirrus or clear sky backgrounds. The resulting “cloud mask”, combined with the wind, visibility, and precipitation sensors, assists the software “pseudo-operator” in deciding whether or not to open the observatory dome and begin, continue, or end laser operations. Based on cloud distribution, the “pseudo-operator” can also decide which satellites to track and over what portions of the orbit.

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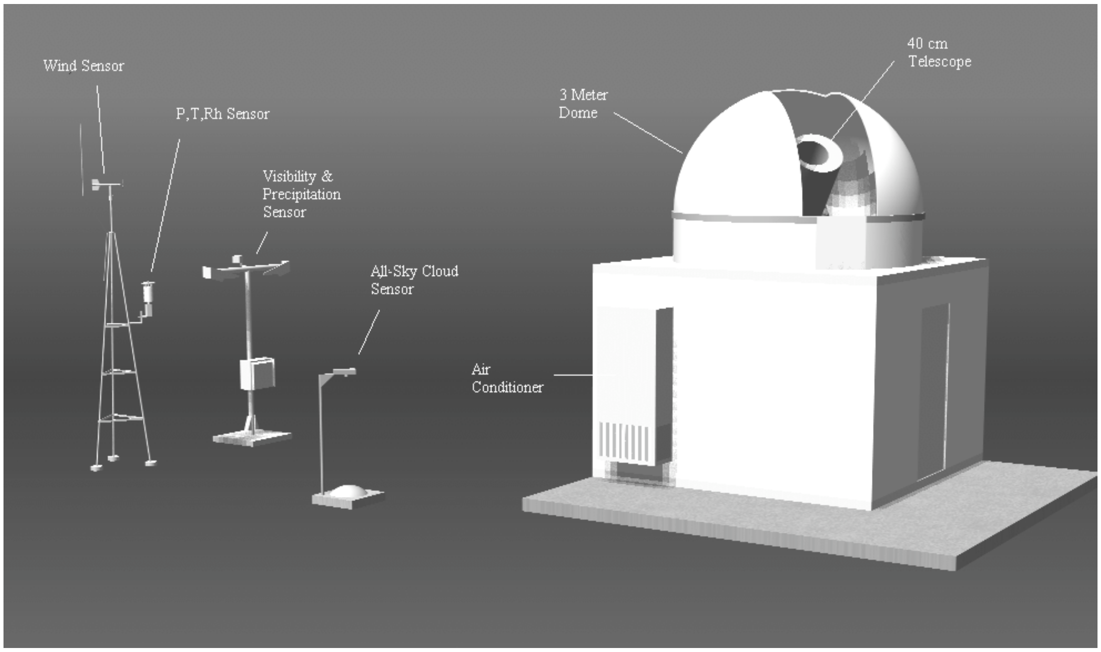

Figure7: Three-dimensional CAD drawing of fielded SLR2000 system.

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2.8 Environmental Shelter and Tracking Dome

The SLR2000 system is protected by the environmental shelter and azimuth tracking dome illustrated in Figure 7. The facility sits on a stable concrete pad. The walls, roof, and floor of the shelter are assembled from prefabricated sheets manufactured by the Bally Corporation and are typically used in building refrigeration boxes. Each wall panel is 10 cm thick and consists of thermally insulating material sandwiched between two aluminum outer surfaces which can be painted or otherwise treated to withstand harsh environments. Besides their excellent insulation and durability, the panels provide a relatively dust free environment and are easy to assemble onsite via interlocking connectors. The 3 meter diameter fiberglass dome, manufactured by Technology Innovations Inc., has a motorized open slit (shutter) and azimuth drive. Both are under computer control and the dome azimuth drive is slaved to the tracking mount azimuth. The electronics room is thermally isolated from the open dome area by a removable ceiling is and maintained at a nominal 23^{o}C by a dual heater/air conditioning system for low operating loads and redundancy. This stabilizes the temperature of critical elements in the optical transceiver and timing electronics and provides a comfortable workplace for visiting maintenance personnel.

Outside ambient air and heated air from the electronics room are dehumidified and mixed to maintain the telescope slightly above ambient when the dome is closed in order to minimize thermal gradients and prevent water condensation upon opening the dome. Inexpensive security devices automatically detect, record, and report threats to system security via Internet and/or recorded telephone messages. These include motion and intrusion sensors and surveillance cameras for detecting and reporting unauthorized personnel in the vicinity, thermal sensors for detecting heat pump failure, power/voltage monitors, etc. Key security components, such as the computer and selected sensors, are protected by UPS, and the safe default mode for key subsystems will be “Power Off” in the event of a power failure. The prototype shelter is scheduled to be completed by April 1999.

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